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SPATIAL AND TEMPORAL COHERENCE OF A 35 GHZ GYROMONOTRON USING T--ETC(U)
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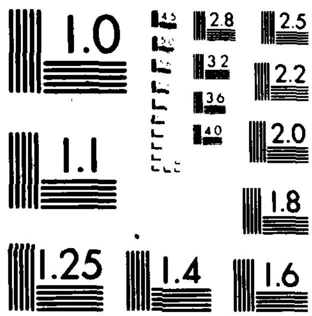

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The characteristics of a 35 GHz oscillator operating with the TE_{01} circular waveguide mode are described. The device produced 147 kW, with an efficiency of 31% at 100 kW. The total radiated energy was 2 KJ per pulse. The spectral coherence appears to be equal to those of other high quality microwave tubes. The mode purity is greater than 95%.

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CONTENTS

SPATIAL AND TEMPORAL COHERENCE OF A 35 GHz GYROMONOTRON USING THE TE_{01} CIRCULAR MODE

INTRODUCTION

There has been considerable recent interest in cyclotron masers (commonly called gyrotrons) for the production or amplification of high power millimeter wavelength radiation.(1-5) These devices have demonstrated higher efficiency and average power capabilities at higher frequencies (28-330 GHz) than conventional microwave tubes.(6-8) One class of these devices, the single cavity oscillator (gyromonotron) is of interest for radar and to the fusion community for electron cyclotron heating.(9-12) Several of these devices have been realized, with the highest power (1 MW at 3.5 mm) reported by Flyagin(2) in the USSR.

In this letter we describe a gyromonotron operating at 35 GHz with an output power of 147 kW. This device is the first gyrotron reported at this frequency and is unique in that it operates in the TE_{01} (circular) mode, which is readily converted to a linearly polarized rectangular mode. The gyrotron was specifically designed as a source for electron cyclotron heating (ECH) experiments in tokamaks, and thus has a long pulse length (20 ms), and utilizes the TE_{011} mode. This latter feature allows the linear polarization of the radiation with a commercial mode converter and will permit the examination of the effect of polarization in ECH experiments. We also report for the first time measurements of the temporal and spatial coherence of a gyromonotron.

Design

The operating parameters of the gyromonotron were determined using the linear theory of Chu(13) and non-linear calculations employing an orbit integrator developed originally by Drobot(14) and modified by the authors.

The device parameters are given in Table 1. A schematic is shown in Figure 1. To produce the electron beam a magnetron type electron gun designed by Seftor et al(15) was used. The magnetic field for both the gun and microwave interaction

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regions was produced by a superconducting solenoid. The field at the cavity was approximately 13.2 kGauss.

The cavity was modified right-circular, with the profile shown in Figure 2a, supporting an electromagnetic field with an electric field profile given in Figure 2b. This profile was measured in the cavity in the absence of the electron beam. The taper, given in Figure 2a, was expected to give some improvement in efficiency but was chosen rather arbitrarily, and is not necessarily optimal.[16-20] As in most gyromonotrons,[1] the wave frequency was just slightly above cut-off, and the length was 3.3 free space wavelengths. This length was shorter than that for optimum efficiency (equal to 5.5 λ) in order to maximize the output wave power without operating near the diffraction limited Q.[21] The use of a very low Q was rejected since it was expected that the device would then be influenced excessively by external reflections, which in the case of ECH experiments were of unknown magnitude. Enhancement of the Q over the diffraction limit was produced by a small iris and an abrupt step to the output guide diameter at the output of the cavity.

The output guide was 0.80 cm in radius, a value such that the TE_{02} mode was cut off at 35 GHz. This eliminated the most likely form of mode conversion at the output of the cavity. Two different collector geometries were tried. For short pulses (1 μsec) the collector was formed by the output guide, while the 20 msec version required a 5 cm diameter collector. No difference in the performance of the tube was observed (other than the ability to dissipate beam energy) with the two collectors. The output window was a tuned disk of Beryllia.

The mode converter was of the type manufactured by Hitachi.[22] It was found to be capable, with pressurization of 2 atm. of SF_6, of withstanding breakdown to more than 147 kW.

Results

A maximum power of 147 kW was produced, with an efficiency of 31% achieved at 100 kW. (With the large diameter collector, pulses of up to 20 msec were achieved with an output of 100 kW, yielding a total radiated energy of 2 kilojoules.)

The behavior of the device with variations of the beam current and the magnetic field can be compared with theory. Figure 3 shows both the calculated and experimentally observed efficiency as a function of the beam current for optimized magnetic fields. (Here the efficiency of the device is defined as the ratio of the output power to the beam power.) The theoretical efficiencies have been calculated with allowance for cavity, output guide, and window losses, which are expected, in the experimental device, to amount to 12%.

Two theoretical curves are given, corresponding to different values for α, the ratio of the perpendicular to parallel beam electron velocities. The design value for α for the electron gun used in the experiment was 1.5, but small variations in the applied voltages and magnetic fields could result in an α as high as 1.8.[15] (No direct measurement of this parameter has been made.) Additionally, we note that the electromagnetic fields used in the calculation were those of an unperturbed right-circular cavity. These fields are a close approximation to those measured in cold tests, but may not be those existing in the presence of the beam. With the inclusion of these uncertainties, and an estimate of experimental errors, the observed and predicted results are in reasonable agreement.

We note that the peak in efficiency occurs for a beam current of 3 Amperes, and that the efficiency drops to 0.24 for 9 Amperes. The strength of the interaction, and therefore the efficiency, is determined by the magnitude of the

RF electric field strength in the cavity, which is in turn determined by the beam current and cavity Q. Straightforward arguments show that the efficiency will remain constant for a constant value of QI. It is therefore clear that for higher power operation, a lower value of Q is required.

In order to evaluate the effect of changing Q, operation was also attempted with quality factors of 400 and 1600. As expected, a Q of 1600 yielded the same efficiency as that of 800 (Figure 3) but at a current of 1.8 Amperes. Operation with a Q of 400 was plagued by the appearance of a parasitic oscillation in the input guide, as the starting currents for this and the desired cavity mode appeared to be approximately equal. The maximum efficiency for this case was 0.17, and the operation was extremely erratic. It is postulated that the parasitic oscillation occurred in the TE_{21} mode, since this mode is close to cutoff in the input guide at the observed frequency of 31 GHz.

The Q = 400 oscillator also appeared to be sensitive to reflections at the output. Further investigation is desirable to determine if this is due to the low value of Q, since, as is mentioned above, even lower values of Q are required to reach higher output powers.

Figure 4 shows the dependence of both the observed and the theoretically predicted efficiencies on the magnitude of the magnetic field at the cavity for a beam current of 3 Amperes. Agreement between theory and experiment appears good for high values of the field magnitude, but poor for low values. The reason for the discrepancy is not clear, although it may be due to variations of the gun performance with changes in the magnetic field.

<u>Effect of Beam Velocity Spread</u>

The electron gun is predicted to have a spread in velocities parallel to the magnetic field of approximately 11[15] to 15[5] percent. Initial calculations indicate that the oscillator operation should be substantially unaffected by velocity distributions below 20%. The agreement between the theoretical and observed efficiency supports these calculations. We note that this tolerance to relatively high velocity spreads may be a fundamental difference between the gyrotron oscillator and the gyrotron travelling wave amplifier, as it is theoretically predicted[5] that the amplifier may require much higher quality beams for efficient operation.

Spectrum and Mode Purity

With the oscillator operating in the long pulse (10 msec) mode, it was possible to obtain a spectrum of the output radiation by sweeping a frequency analyzer during a single pulse. The result, shown in Figure 5, indicates a line width of 1.5 MHz. (This gives a maximum line width of 4 parts in 10^5.) This appears to be an upper bound, since it was observed that the frequency variations during the analyzer sweep were of the same order. These variations were measured by manually sweeping the analyzer so that different points in the pulse could be observed on a shot-to-shot basis. The variations appeared to be well correlated with modulator voltage fluctuations.

A measure of the mode purity was obtained by observing output power directly in the TE_{01} mode with a calorimeter, with and without a filter preceding the calorimeter. The filter consisted of a tightly wound helix waveguide which strongly attenuated all modes other than the TE_{01} and was cut off to the TE_{02} mode. No difference in the output power was observed when the filter was inserted. This measurement of the power was also in agreement with that mode using the Hitachi mode converter and a calibrated cyrstal in a WR-28 mount. The mode impurity can then be inferred to be less that 5%, the accuracy of the calorimeter.

Conclusion

The oscillator has been shown to operate as theoretically predicted, and at power levels and pulse lengths useful for ECH and radar applications. Linear polarization of the TE_{01} radiation is straightforward for these powers and pulse lengths. Efficient operation was achieved with little difficulty, although attempts at high power via lower Q factors met with problems in the form of parasitic oscillations and reflections from the load. These difficulties will have to be overcome in order to realize higher power devices. The device has a spectral purity at least comparable with other high quality microwave sources, and appears to be presently limited only by modulator voltage variations.

Acknowledgments

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22. Hitachi Dinshi, LTD, Model R6414.

Table 1

Gyromonotron Design Parameters

Beam Voltage	70 kV
Beam Current	4 - 10 Amperes
Frequency	35 GHz
Cavity Length	2.86 cm
Maximum Cavity Radius	0.53 cm
Cavity Q	800
Cavity Mode	TE_{011} (modified)

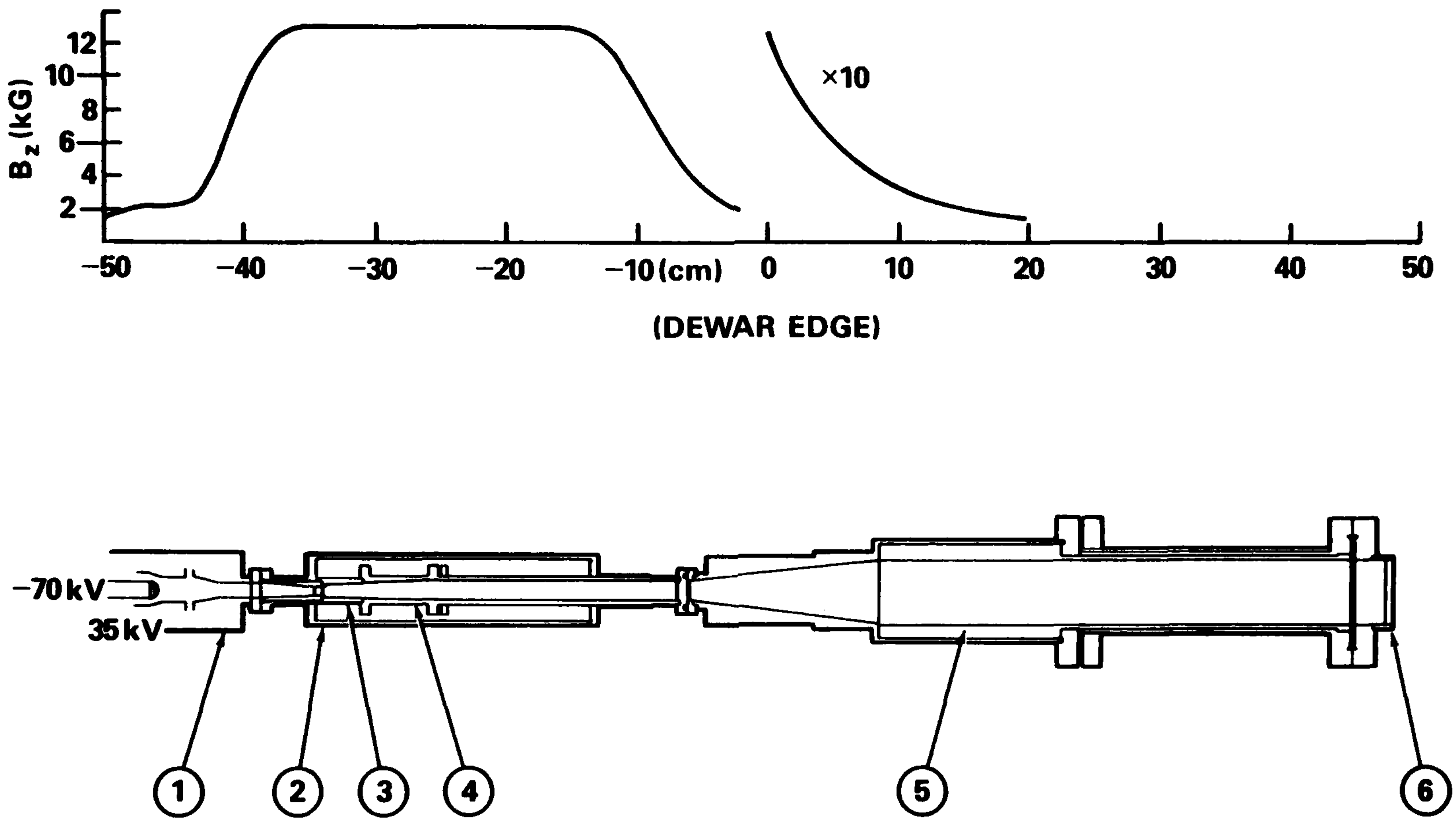
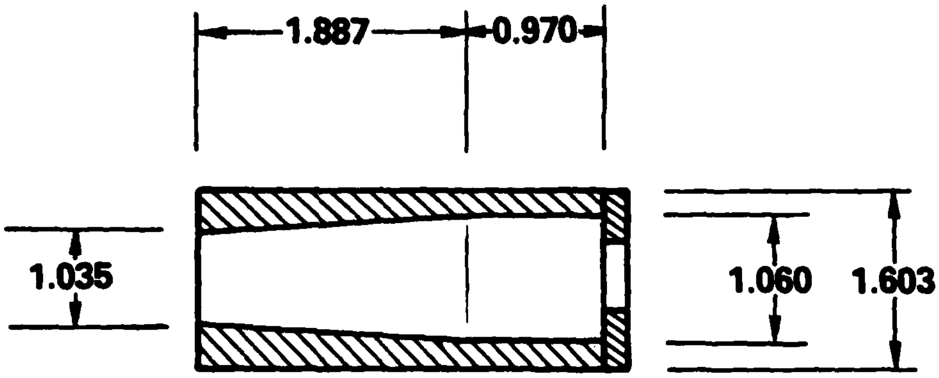
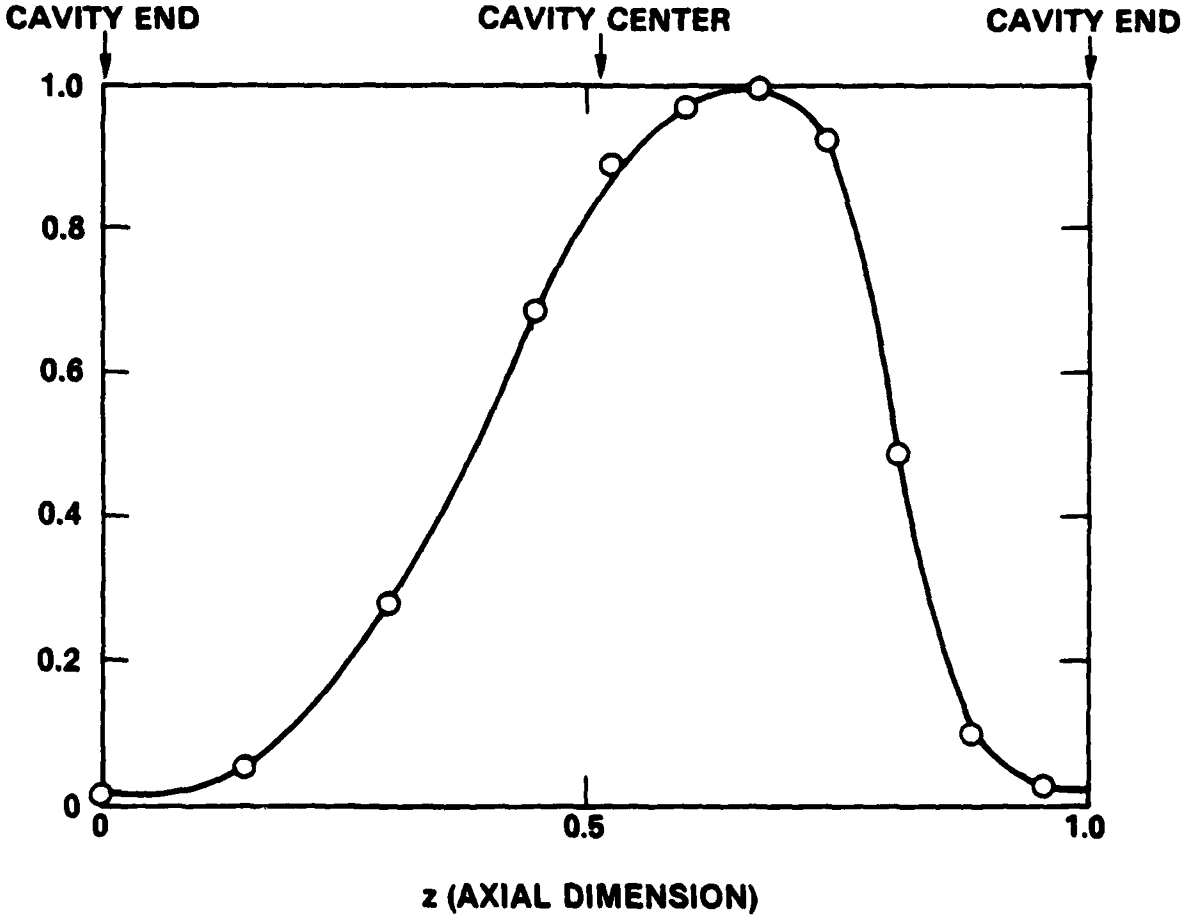


Fig. 1 — Schematic of the long pulse 35 GHz oscillator (1) electron gun, (2) vacuum envelope, (3) cavity, (4) output guide, (5) collector, and (6) output window



(a) Diagram of the cavity used for the Q = 800 oscillator cavity
(the dimensions are in centimeters)



(b) Electric field profile for the cavity of 2(a)

Figure 2

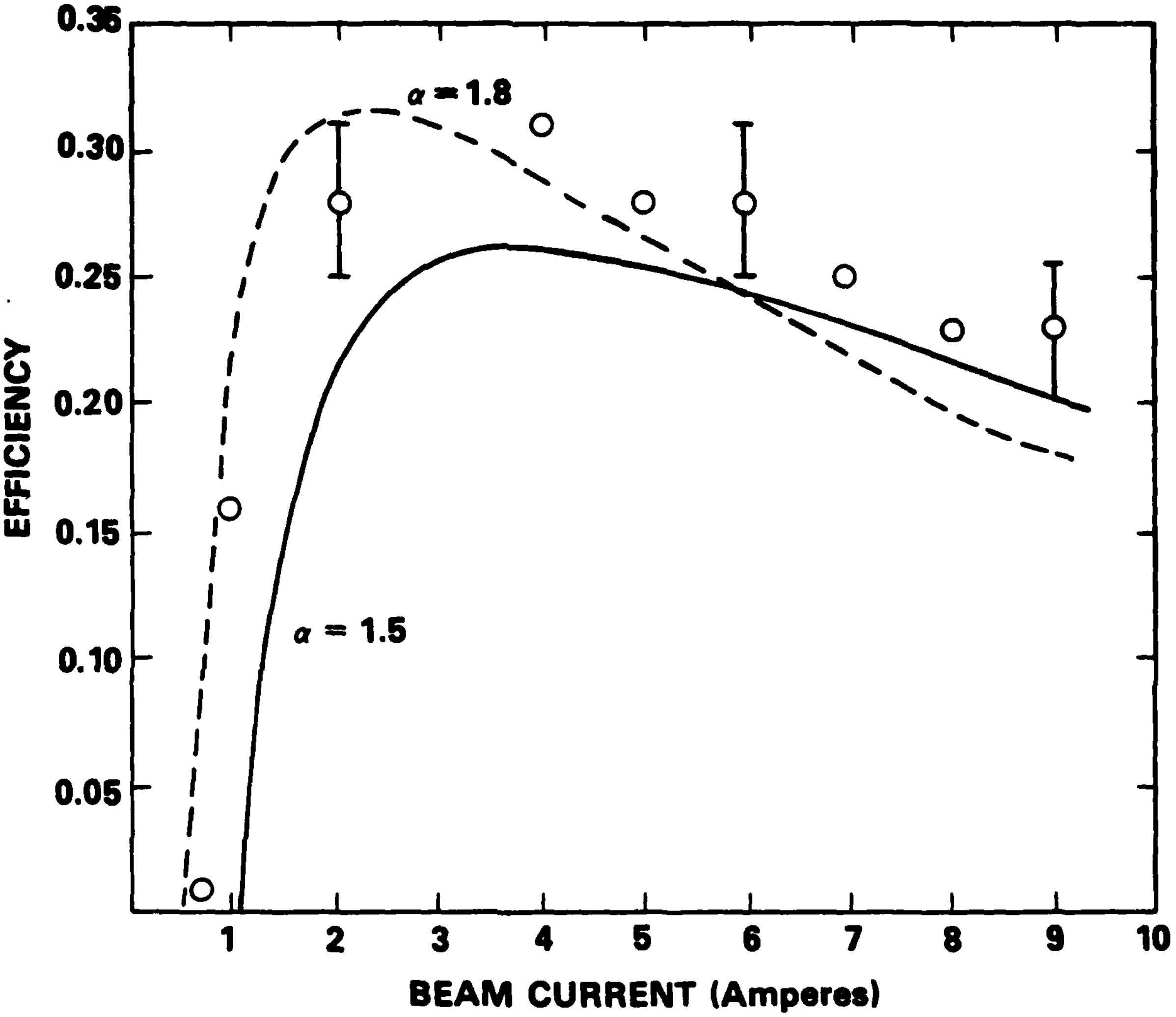


Fig. 3 — Output efficiency of the oscillator with Q = 800 as a function of beam current. The magnetic field at the cavity has been optimized for each point. The two curves were generated by the code, using different values of α.

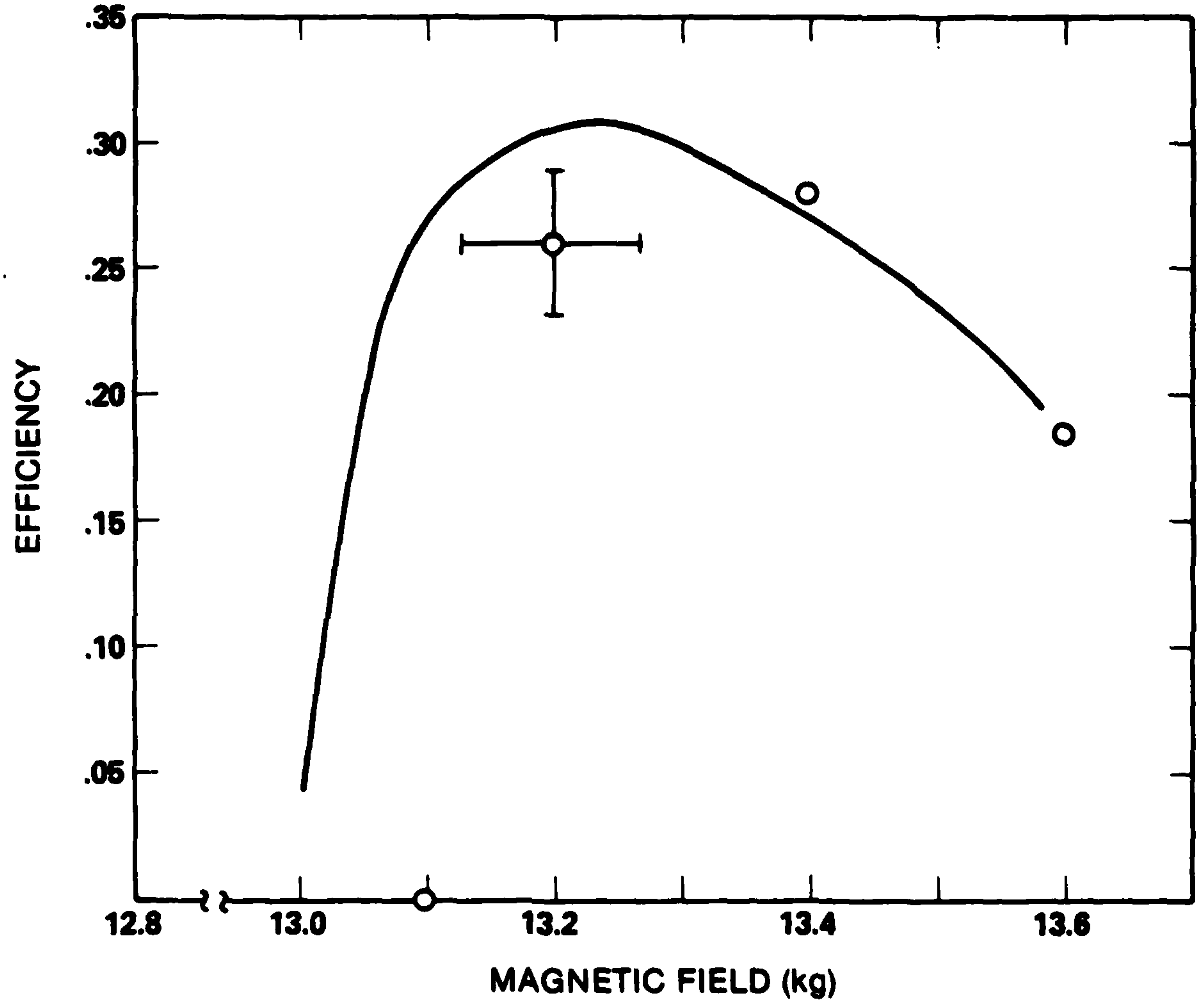


Fig. 4 — Output efficiency of the oscillator with Q = 800 as a function of the magnetic field amplitude at the cavity, for a beam current of 3 amperes

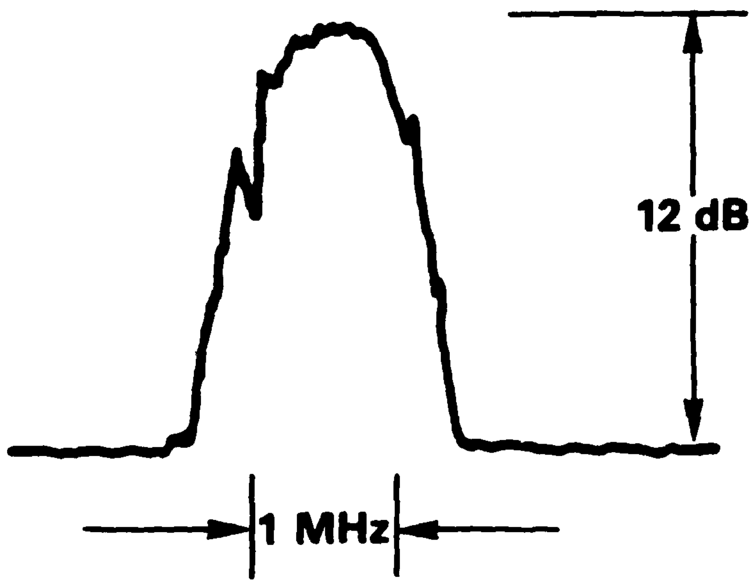


Fig. 5 — Spectrum of the oscillator. The spectrum analyzer sweep time was short compared to the pulse length; therefore, this is a CW spectrum

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